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Zimmanck

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(54) **AUTONOMOUS CHARGE BALANCING OF DISTRIBUTED AC COUPLED BATTERIES WITH DROOP OFFSET**

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(Continued)

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H02J 7/00 (2006.01)
H02J 7/14 (2006.01)
(Continued)

(52) **U.S. Cl.**
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(Continued)

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(Continued)

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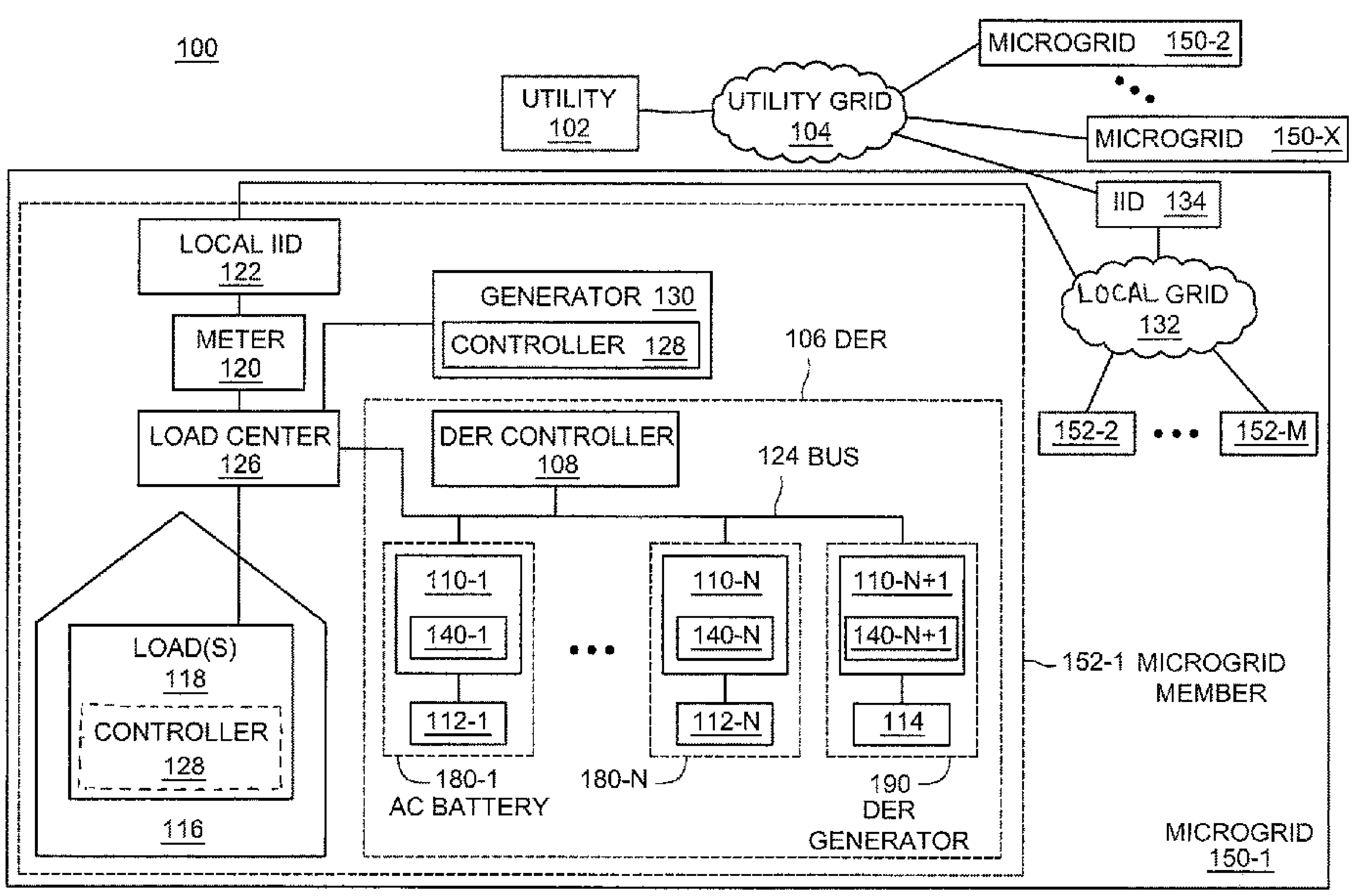
(57) **ABSTRACT**

A method and apparatus for autonomous charge balancing of an energy storage device of the microgrid. In one embodiment the method comprises obtaining, at a droop control module of a power conditioner coupled to an energy storage device in a microgrid, an estimate of a state of charge (SOC) of the energy storage device; introducing a bias, the bias based on (I) the estimate of the SOC and (II) a target SOC value for each energy storage device of a plurality of energy storage devices in the microgrid, to a droop control determination made by the droop control module; and generating, by the power conditioner, an output based on the droop control determination.

20 Claims, 6 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/369,876, filed on Dec. 5, 2016, now Pat. No. 10,511,178.

(60) Provisional application No. 62/262,696, filed on Dec. 3, 2015.

(51) **Int. Cl.**
H02J 3/32 (2006.01)
H02J 13/00 (2006.01)
H02J 7/35 (2006.01)

(52) **U.S. Cl.**
CPC ***H02J 7/0045*** (2013.01); ***H02J 7/0048*** (2020.01); ***H02J 7/35*** (2013.01); ***H02J 13/00007*** (2020.01); *Y02E 40/70* (2013.01); *Y02E 60/00* (2013.01); *Y04S 10/123* (2013.01); *Y04S 10/14* (2013.01); *Y04S 40/121* (2013.01)

(58) **Field of Classification Search**
USPC 320/109
See application file for complete search history.

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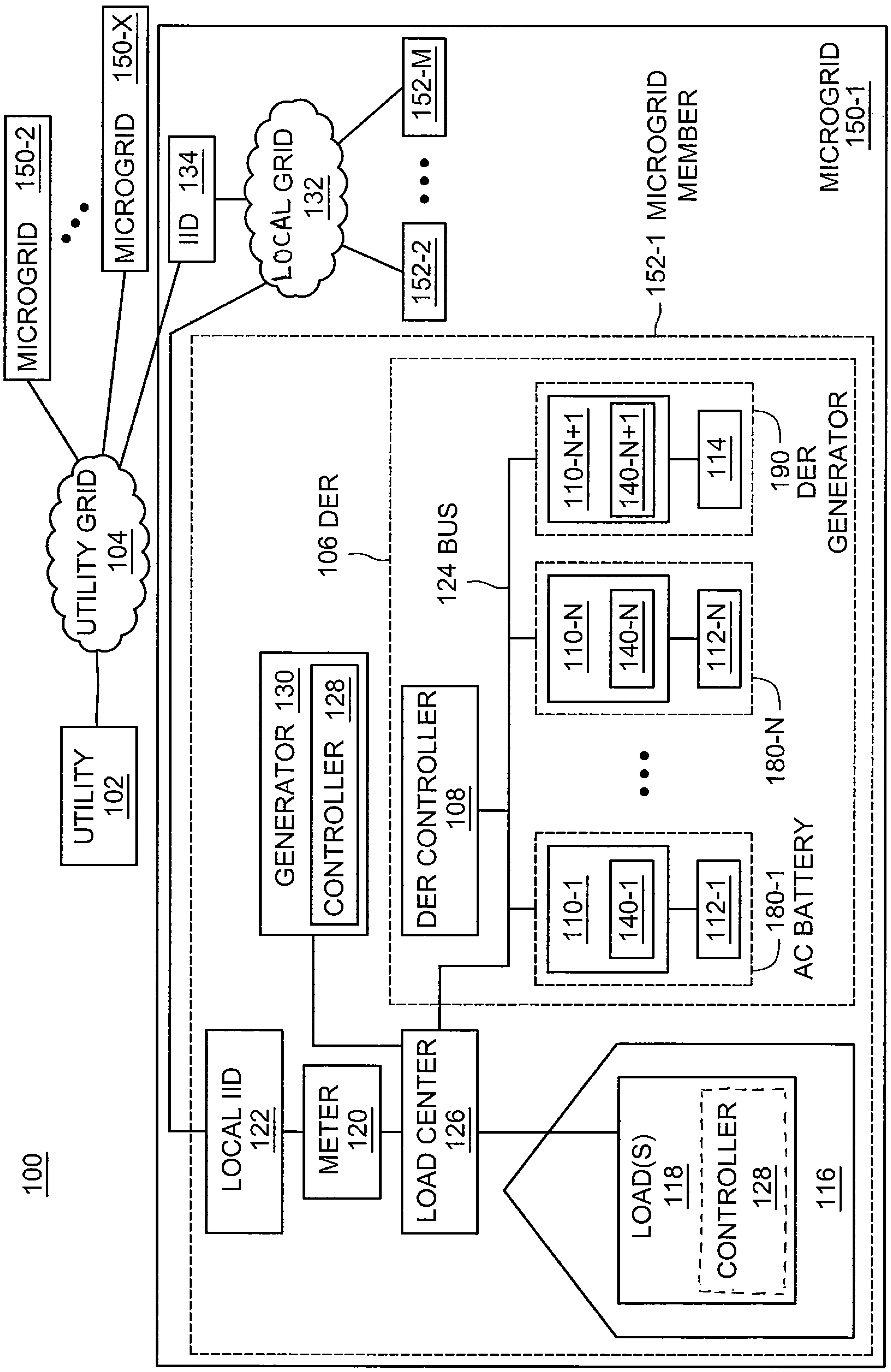
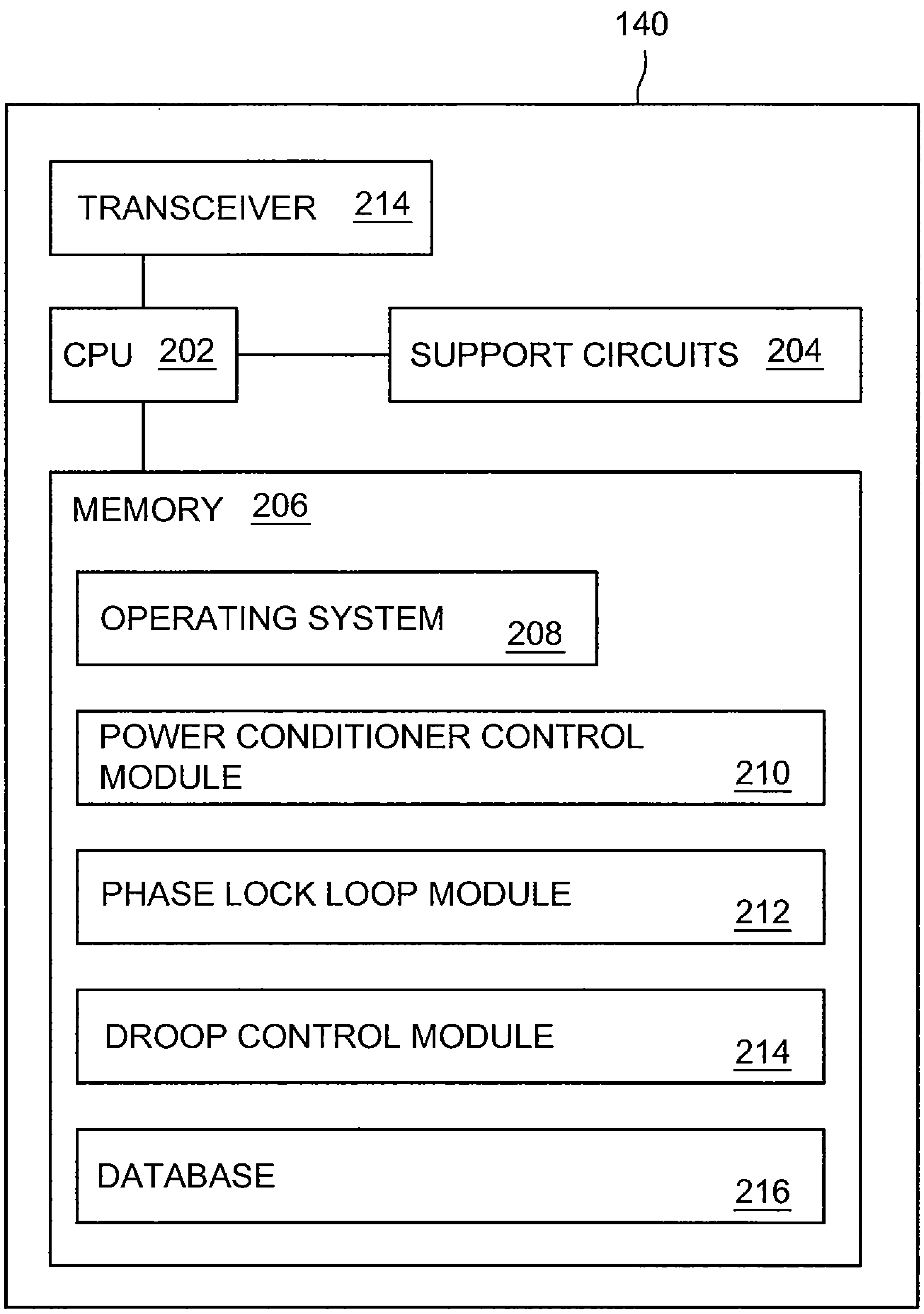


100
UTILITY 102
UTILITY GRID 104
MICROGRID 150-2
MICROGRID 150-X
IID 134
LOCAL GRID 132
152-2
152-M
152-1 MICROGRID MEMBER
MICROGRID 150-1
LOCAL IID 122
METER 120
LOAD CENTER 126
GENERATOR 130
CONTROLLER 128
DER CONTROLLER 108
106 DER
124 BUS
110-1
140-1
112-1
180-1 AC BATTERY
110-N
140-N
112-N
180-N
110-N+1
140-N+1
114
190 DER GENERATOR
LOAD(S) 118
CONTROLLER 128
116

FIG. 1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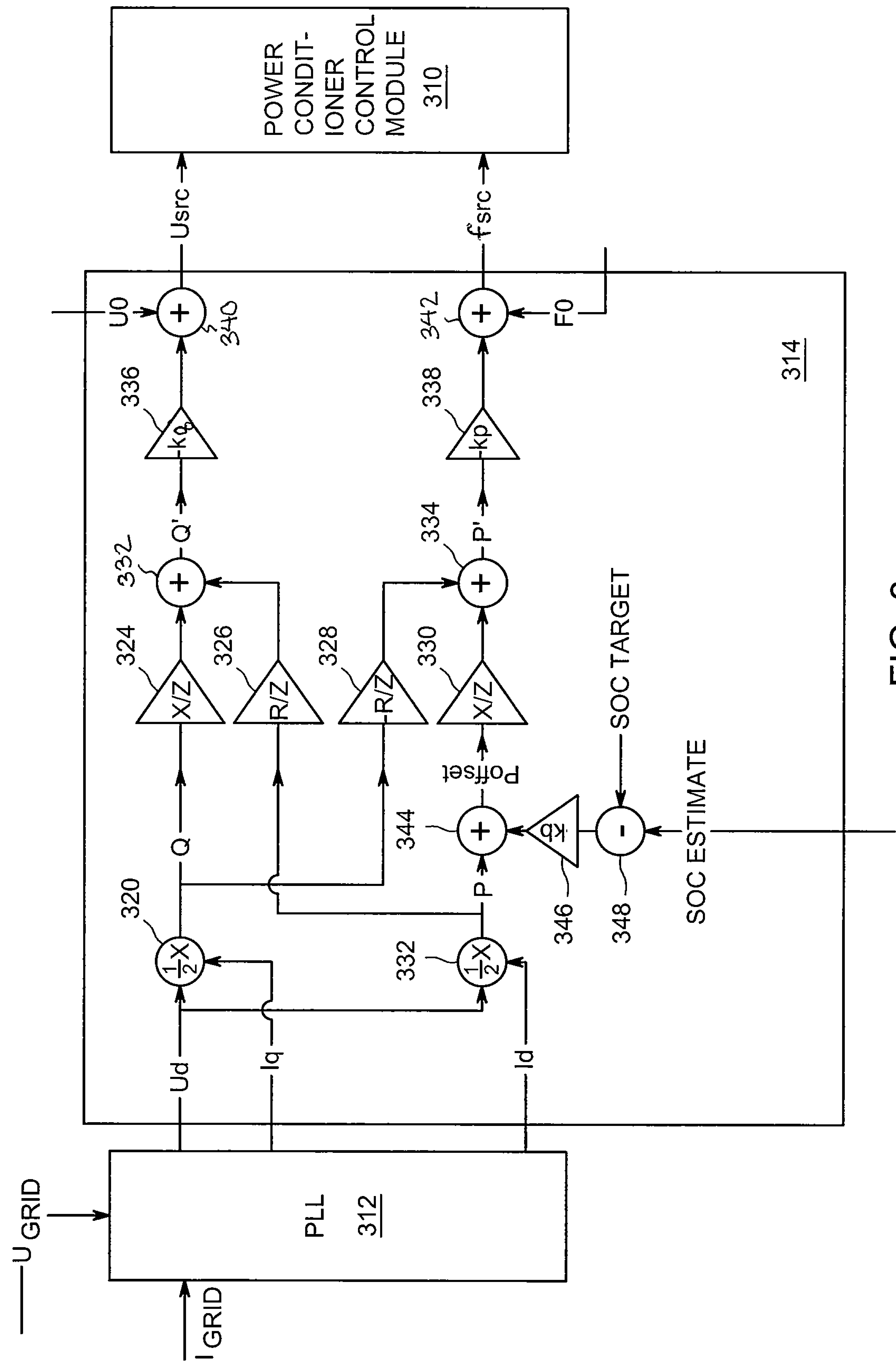
TRANSCEIVER 214
CPU 202
SUPPORT CIRCUITS 204
MEMORY 206
OPERATING SYSTEM 208
POWER CONDITIONER CONTROL MODULE 210
PHASE LOCK LOOP MODULE 212
DROOP CONTROL MODULE 214
DATABASE 216

FIG. 2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Usrc
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U0
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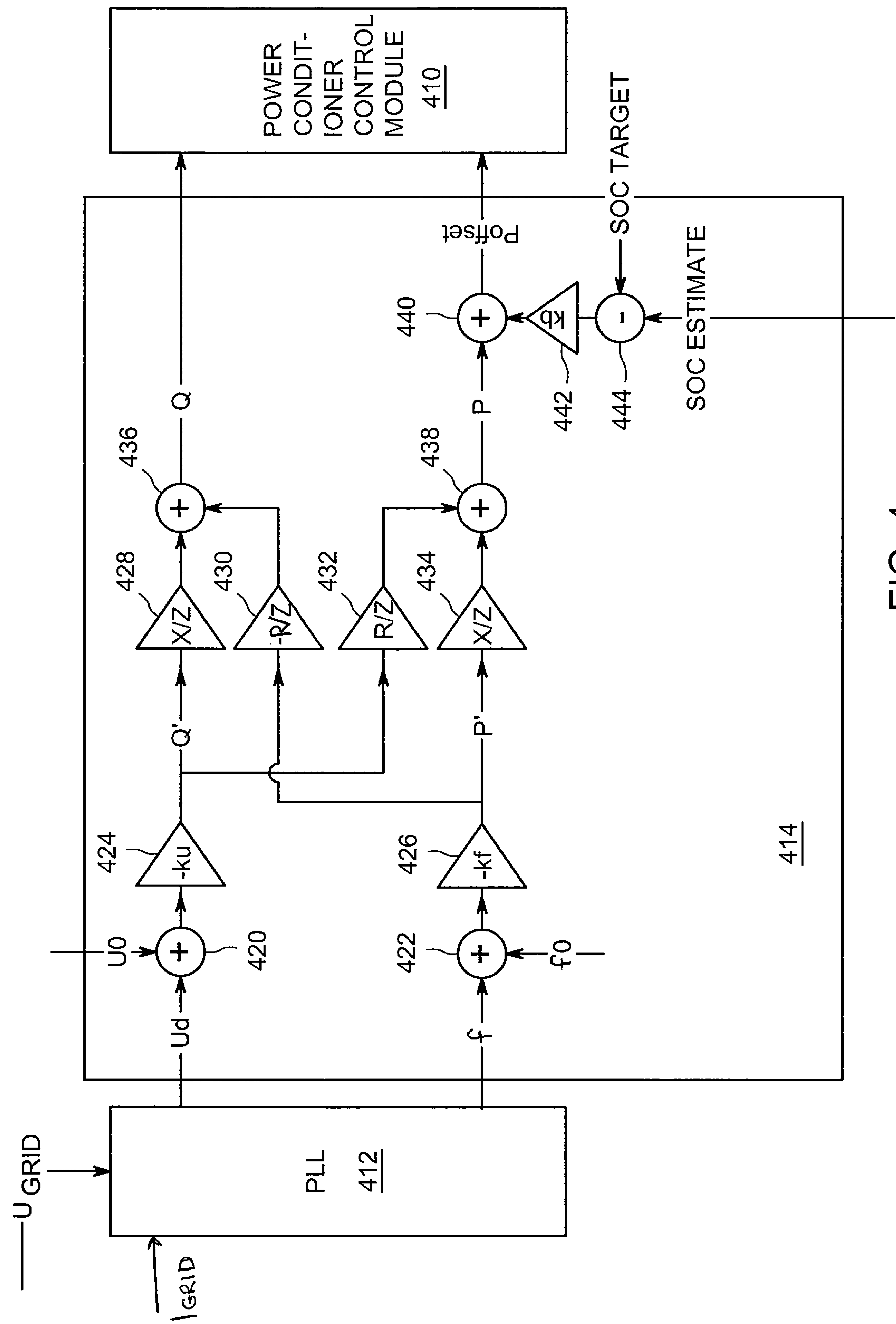
F0
336
338
kq
kp
314
Q'
P'
332
334
324
326
328
330
X/Z
R/Z
R/Z
X/Z
SOC TARGET
Poffset
Q
344
kb
320
P
SOC ESTIMATE
332
346
348
Ud
Iq
Id
PLL 312
U GRID
I GRID

FIG. 3


POWER CONDIT-IONER CONTROL MODULE
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PLL
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414
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Ud
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U0
f0
420
422
-ku
-kf
424
426
Q'
P'
X/Z
-R/Z
R/Z
X/Z
428
430
432
434
436
438
Q
P
440
442
444
kb
Poffset
SOC TARGET
SOC ESTIMATE

FIG. 4

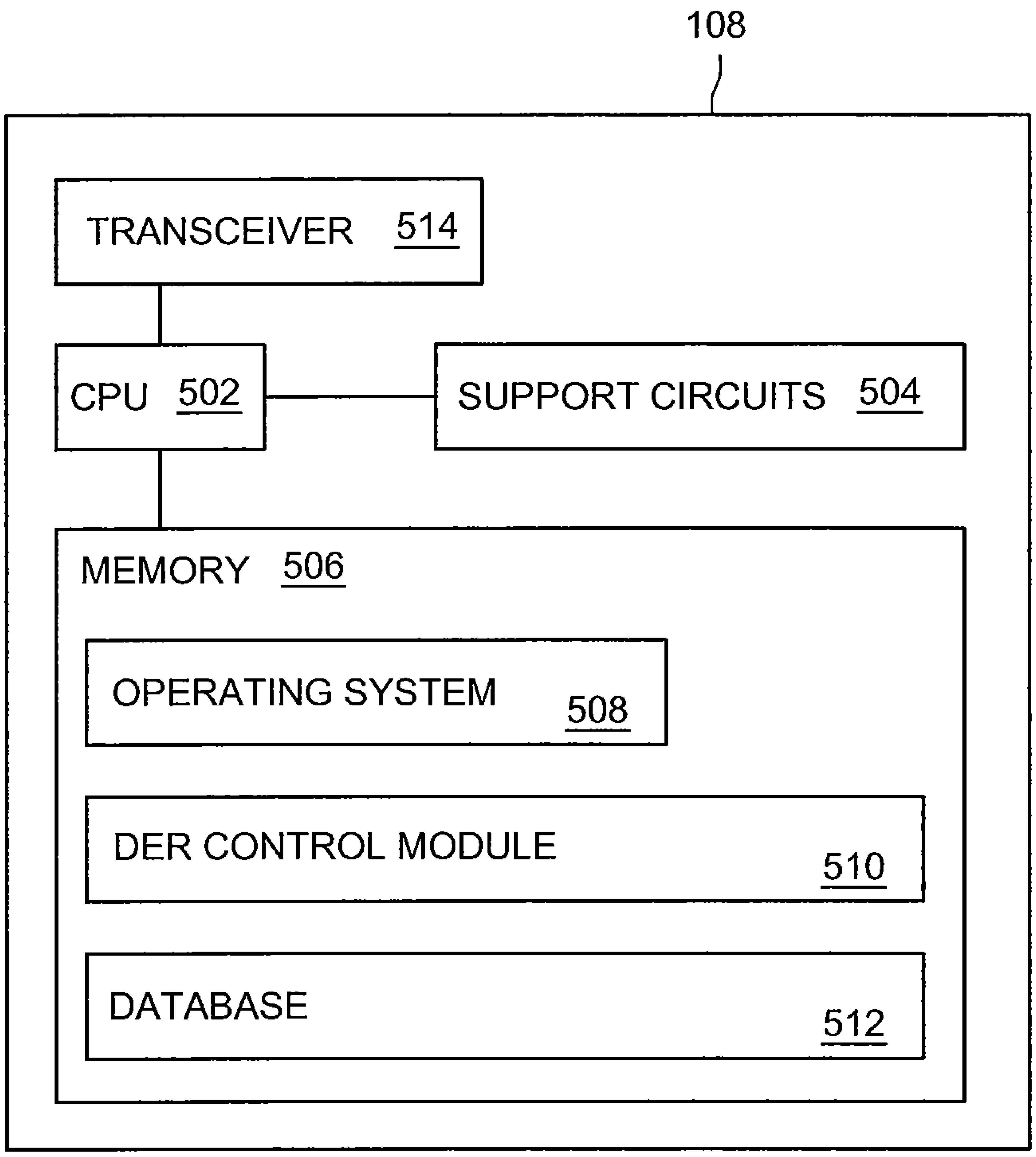
108
TRANSCEIVER 514
CPU 502
SUPPORT CIRCUITS 504
MEMORY 506
OPERATING SYSTEM 508
DER CONTROL MODULE 510
DATABASE 512

FIG. 5

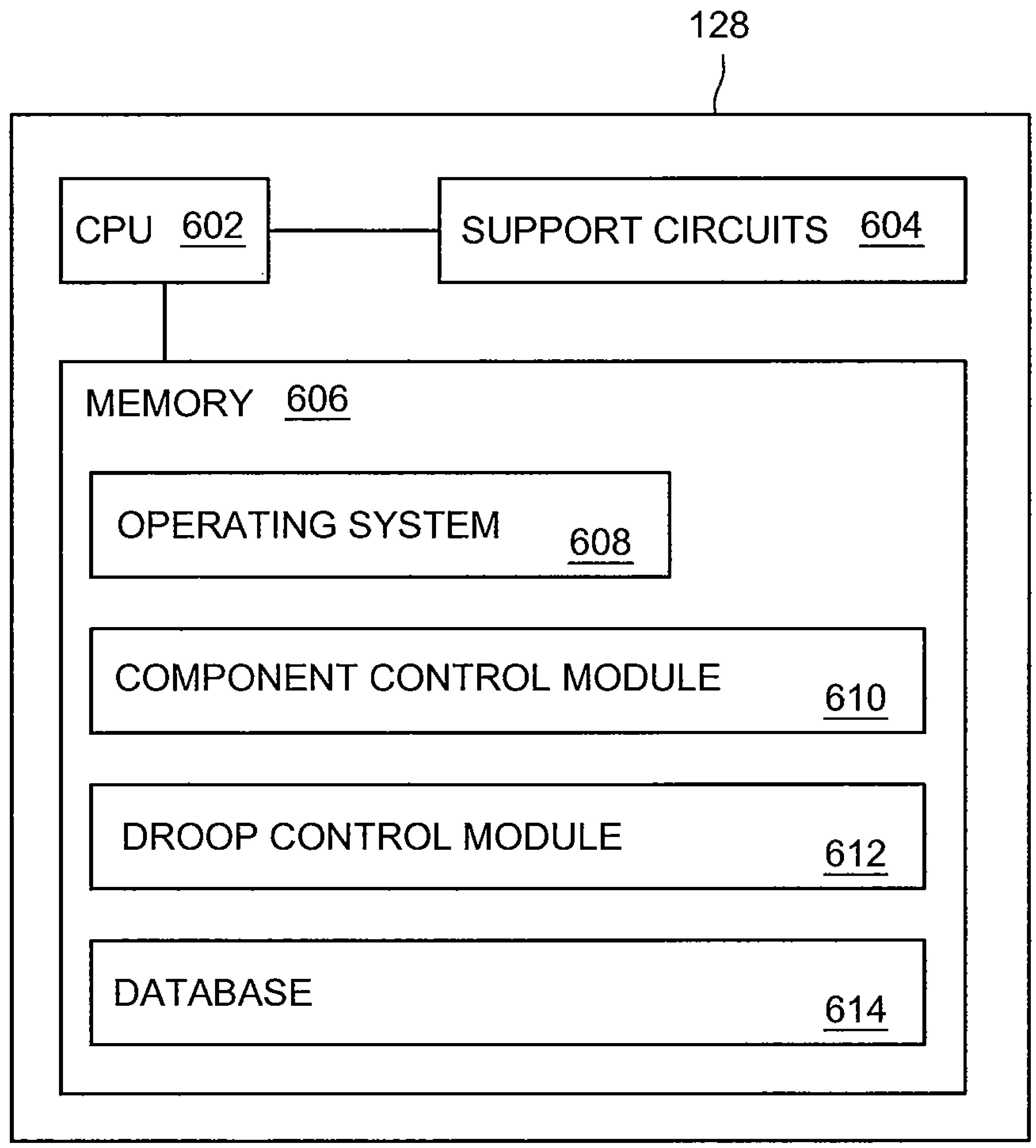
128
CPU 602
SUPPORT CIRCUITS 604
MEMORY 606
OPERATING SYSTEM 608
COMPONENT CONTROL MODULE 610
DROOP CONTROL MODULE 612
DATABASE 614

FIG. 6

AUTONOMOUS CHARGE BALANCING OF DISTRIBUTED AC COUPLED BATTERIES WITH DROOP OFFSET

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/702,530, entitled "Autonomous Charge Balancing of Distributed AC Coupled Batteries with Droop Offset" and filed Dec. 3, 2019, which is a continuation of U.S. patent application Ser. No. 15/369,876 entitled "Autonomous Charge Balancing of Distributed AC Coupled Batteries with Droop Offset" and filed Dec. 5, 2016 (now U.S. Pat. No. 10,511,178, Issued Dec. 17, 2019), which claims priority to U.S. Provisional Patent Application No. 62/262,696, entitled "Autonomous Charge Balancing of Distributed AC Coupled Batteries with Droop Offset" and filed Dec. 3, 2015. Each of the aforementioned patent applications is herein incorporated in its entirety by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

Embodiments of the present disclosure relate generally to charge balancing of batteries and, more particularly, to autonomous charge balancing of AC coupled batteries in a microgrid.

Description of the Related Art

A conventional microgrid generally comprises at least one energy generator, at least one energy storage device, and at least one energy load. When disconnected from a conventional utility grid, a microgrid can generate power as an intentional island without imposing safety risks on any line workers that may be working on the utility grid.

Droop control is one technique that may be used for operating energy storage and generation resources in a microgrid that is disconnected from the utility grid. For several batteries in a microgrid having the same droop characteristics, the batteries will share power equally among each other, or proportional to their power rating. Due to small differences in chemistry, manufacturing tolerances, and the like, the batteries won't charge and discharge at exactly the same rate. In conventional microgrids that rely on communication between microgrid resources when operating in an islanded state, such communication can be used to ensure that the charge among the batteries is balanced. However, if the microgrid communication is interrupted or disabled, the differences among the batteries will cause the batteries to drift apart and the charge among the batteries to become unbalanced.

Therefore, there is a need in the art for a technique for autonomous charge balancing among batteries in a droop-controlled microgrid.

SUMMARY OF THE INVENTION

Embodiments of the present invention generally relate to autonomous charge balancing among batteries in a droop-controlled microgrid as shown in and/or described in connection with at least one of the figures.

These and other features and advantages of the present disclosure may be appreciated from a review of the following detailed description of the present disclosure, along with the accompanying figures in which like reference numerals refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. **1** is a block diagram of a power system in accordance with one or more embodiments of the present invention;

FIG. **2** is a block diagram of a power conditioner controller in accordance with one or more embodiments of the present invention;

FIG. **3** is a block diagram of a droop control module in accordance with one or more embodiments of the present invention;

FIG. **4** is a block diagram of a droop control module in accordance with one or more embodiments of the present invention;

FIG. **5** is a block diagram of a DER controller in accordance with one or more embodiments of the present invention; and

FIG. **6** is a block diagram of a component controller in accordance with one or more embodiments of the present invention.

DETAILED DESCRIPTION

FIG. **1** is a block diagram of a power system **100** in accordance with one or more embodiments of the present invention. This diagram only portrays one variation of the myriad of possible system configurations. The present invention can function in a variety of environments and systems.

The power system **100** comprises a utility **102** (such as a conventional commercial utility) and a plurality of microgrids **150-1**, **150-2**, . . . , **150**-X (collectively referred to as microgrids **150**) coupled to the utility **102** via a utility grid **104**. Through their connections to the utility grid **104**, each microgrid **150** as a whole may receive energy from the utility grid **104** or may place energy onto the utility grid **104**. In some embodiments, coupling energy to a commercial utility grid is strictly controlled by regulation and it is beneficial that the microgrids **150** maintain or strive to maintain a zero energy output policy. Each microgrid **150** is capable of operating without energy supplied from the utility **102** and may cover a neighborhood, a village, a small city, or the like, as the term "microgrid" is not intended to imply a particular system size.

Although the microgrid **150-1** is depicted in detail in FIG. **1** and described herein, the microgrids **150-2** through **150**-X are analogous to the microgrid **150-1**. However, the number and/or type of various microgrid components may vary among the microgrids **150**.

The microgrid **150-1** comprises a plurality of microgrid members **152-1**, **152-2**, . . . , **152**-M (collectively referred to as microgrid members **152**) coupled to a local grid **132** which in turn is coupled to the utility grid **104** via an island interconnect device (IID) **134**. The local grid **132** may be a trunk of the utility grid **104** or it may be a specifically designed local grid for the microgrid **150-1**.

The IID **134** determines when to disconnect/connect the microgrid **150-1** from/to the utility grid **104** and performs the disconnection/connection. Generally, the IID **134** comprises a disconnect component (e.g., a disconnect relay) along with a CPU (not shown) and an islanding module (not shown) and monitors the utility grid **104** for failures or disturbances, determines when to disconnect from/connect to the utility grid **104**, and drives the disconnect component accordingly. For example, the IID **134** may detect a fluctuation, disturbance or outage with respect to the utility grid **104** and, as a result, disconnect the microgrid **150-1** from the utility grid **104**. The IID **134** may also disconnect the microgrid **150-1** from the utility grid **104** when the microgrid **150-1** is either overproducing energy or overloading the utility grid **104**. Once disconnected from the utility grid **104**, the microgrid **150-1** can continue to generate power as an intentional island without imposing safety risks on any line workers that may be working on the utility grid **104**. In some embodiments, the IID **134** may receive instructions from another component or system for disconnecting from/connecting to the utility grid **104**.

The microgrid member **152-1** comprises a building **116** (e.g., a residence, commercial building, or the like) coupled to a load center **126** which may be within or outside of the building **116**. The load center **126** is coupled to the local grid **132** via a utility meter **120** and a local IID **122**, and is further coupled to a distributed energy resource (DER) **106**, a generator **130**, and one or more loads **118** for coupling power among these components. Although the microgrid member **152-1** is depicted in detail in FIG. **1** and described herein, the microgrid members **152-2** through **152**-M are analogous to the microgrid member **152-1**. However, the number and/or types of various microgrid member components may vary among the microgrid members **152**.

The local IID **122** determines when to disconnect/connect the microgrid member **152-1** from/to the local grid **132** and performs the disconnection/connection. For example, the local IID **122** may detect a grid fluctuation, disturbance or outage and, as a result, disconnect the microgrid member **152-1** from the local grid **132**. The IID **122** may also disconnect the microgrid member **152-1** from the local grid **132** when the microgrid member **152-1** is either overproducing energy or overloading the local grid **132**. Once disconnected from the local grid **132**, the microgrid member **152-1** can continue to generate power as an intentional island without imposing safety risks on any line workers that may be working on the local grid **132**. The local IID **122** comprises a disconnect component (e.g., a disconnect relay) for physically disconnecting from/connecting to the local grid **132**. The local IID **122** may additionally comprise a CPU (not shown) and an islanding module (not shown) for monitoring grid health, detecting grid failures and disturbances, determining when to disconnect from/connect to the local grid **132**, and driving the disconnect component accordingly. In some embodiments, the local IID **122** may receive instructions from another component or system for disconnecting from/connecting to the local grid **132**.

The meter **120** measures the ingress and egress of energy for the microgrid member **152-1**; in some embodiments, the meter **120** comprises the IID **122** or a portion thereof. The meter **120** generally measures real power flow (kWh), reactive power flow (kVAR), grid frequency, and grid voltage (referred to herein as the measured parameters). In certain embodiments these measured parameters may be communicated to a microgrid monitoring system (not shown) that monitors each of the microgrid members **152**.

The generator **130** is an energy generator, such as a diesel generator, that automatically increases or curtails energy output depending on the needs of the microgrid member **152-1**. The generator **130** comprises a component controller **128**, described in detail further below with respect to FIG. **5**. The component controller **128** may optimize the operation of the generator **130** with respect to the microgrid member **152-1** and/or the microgrid **150-1** (e.g., by generating control instructions for the generator **130**); implement control instructions for operating the generator **130** (e.g., instructions received from another component or system); obtain data pertaining to the generator **130** (e.g., performance data, operational data, or the like) which may further be communicated to another component or system; or perform similar functions.

The loads **118** consume energy obtained via the load center **126** and may be located inside of the building **116** or outside of the building **116**. Some of the loads **118** may be "smart loads" that comprise a corresponding component controller **128** for optimizing the utilization of energy (e.g., disconnecting/connecting the smart load **118** when the grid is overloaded/underloaded, modulating operation of smart loads **118**, such as HVAC, pumps, and the like, as needed); implementing control instructions for the load **118** (e.g., instructions received from another component or system); obtaining data pertaining to the loads **118** (e.g., performance data, operational data, and the like) which may further be communicated to another component or system; or performing similar functions.

One or more of the smart loads **118** may be an energy storage component that stores energy received via the load center **126**, such as a hot water heater, an electric car, or the like. Such energy storage loads **118** may further deliver stored energy to other loads **118** and/or the local grid **132** as needed, where the energy storage and delivery is controlled by the corresponding component controller **128**.

The DER **106** comprises power conditioners **110-1** . . . **110**-N, **110**-N+1 coupled in parallel to a bus **124** that is further coupled to the load center **126**. Generally the power conditioners **110** are bi-directional power conditioners and those power conditioners **110** in a first subset of power conditioners **110** are coupled to DC energy sources **114** (for example, renewable energy sources such as wind, solar, hydro, and the like) while the power conditioners **110** in a second subset of power conditioners **110** are coupled to energy storage devices **112** as described below. The combination of a DC energy source **114** and a corresponding power conditioner **110** may be referred to herein as a DER generator. In embodiments where the power conditioners **110** are DC-AC inverters, a power conditioner **110** and a corresponding energy storage device **112** may together be referred to herein as an AC battery **180**; in embodiments where the power conditioners **110** are DC-DC converters, a power conditioner **110** and a corresponding energy storage device **112** may together be referred to herein as a battery DC supply.

In the embodiment depicted in FIG. **1**, the power conditioners **110-1** . . . **110**-N are respectively coupled to energy storage devices **112-1** . . . **112**-N to form a plurality of AC batteries **180-1** . . . **180**-N, respectively. The AC battery power conditioners **110** convert AC power from the bus **124** to energy that is stored in the corresponding energy storage devices **112**, and can further convert energy from the corresponding energy storage devices **112** to commercial power grid compliant AC power that is coupled to the bus **124**. An energy storage device **112** may be any suitable energy storage device having a "charge level", such as a battery, flywheel, compressed air storage, or the like, that can store energy and deliver the stored energy.

As further depicted in FIG. **1**, the power conditioner **110**-N+1 is coupled to a DC energy source **114** (e.g., a renewable energy source such as wind, solar, hydro, and the like), forming a DER generator, for receiving DC power and generating commercial power grid compliant AC power that is coupled to the bus **124**. In one or more embodiments, the DC energy source **114** is a photovoltaic (PV) module. Although a single DER generator **190** is depicted in FIG. **1**, other embodiments may comprise fewer for more DER generators **190**. In certain embodiments, multiple DC energy sources **114** are coupled to a single power conditioner **110** (e.g., a single, centralized power conditioner). In one or more alternative embodiments, the power conditioners **110** are DC-DC converters that generate DC power and couple the generated power to a DC bus (i.e., the bus **124** is a DC bus in such embodiments). In such embodiments, the power conditioners **110-1** through **110**-N also receive power from the DC bus and convert the received power to energy that is then stored in the energy storage device **112**.

Each of the power conditioners **110** comprises a power conditioner controller **140** (described in detail further below) having a droop control module for implementing droop control techniques that allow the power conditioners **110** to share the load in a safe and stable manner when the microgrid member **152-1** is disconnected from the utility **102** or the local grid **132**.

The DER **106** comprises a DER controller **108** that is coupled to the bus **124** and communicates with the power conditioners **110** (e.g., via power line communications (PLC) and/or other types of wired and/or wireless techniques). The DER controller **108** may send command and control signals to one or more of the power conditioners **110** and/or receive data (e.g., status information, performance data, and the like) from one or more of the power conditioners **110**. In some embodiments, the DER controller **108** is further coupled, by wireless and/or wired techniques, to a master controller or gateway (not shown) via a communication network (e.g., the Internet) for communicating data to/receiving data from the master controller (e.g., performance information and the like).

In certain embodiments, the DER controller **108** comprises the local IID **122** or a portion of the local IID **122**. For example, the DER controller **108** may comprise an islanding module for monitoring grid health, detecting grid failures and disturbances, determining when to disconnect from/connect to the local grid **132**, and driving a disconnect component accordingly, where the disconnect component may be part of the DER controller **108** or, alternatively, separate from the DER controller **108**. In some embodiments, the DER controller **108** may coordinate with the local IID **122**, e.g., using power line communications.

Although the microgrid member **152-1** is depicted as having a single DER **106** in FIG. **1**, in other embodiments the microgrid member **152-1** may have additional DERs. In one or more alternative embodiments, the DER control **108** and the DER generators are absent from the microgrid member **152-1** and the DER comprises only one or more AC batteries **180**.

Each of the power conditioners **110**, the generator **130**, and any smart loads **118** are droop-controlled such that when the microgrid member **152-1** is disconnected from the local grid **132** or the utility grid **104** (e.g., using the IID **122** and/or the IID **134**) and operating in an autonomous mode, these components employ a droop control technique for parallel operation without the need for any common control circuitry or communication among the components.

In accordance with one or more embodiments of the present invention, the AC battery power conditioners **110** each employ a droop offset proportional to the state of charge of the corresponding energy storage device **112** in order to maintain equal relative states of charge among the AC batteries **180** during autonomous operation. For each AC battery **180**, the droop offset is added to the power term within the power conditioner's droop control module and varies (where a positive power corresponds to power being exported from the DER) with the state of charge of the corresponding energy storage device **112**, causing energy to flow from those AC batteries **180** having higher states of charge into those AC batteries **180** with lower states of charge without disrupting the fundamental stability of the droop control. Such operation autonomously drives the power storage devices **112** toward equal (or substantially equal) states of charge.

For example, if a particular AC battery **180** has a state of charge at 50%, that AC battery **180** operates with its normalized droop function. If that AC battery **180** has a state of charge that is below 50%, its droop will be pushed down proportional to its deviation from 50%, forcing the AC battery **180** to run at a power level offset in the charging direction; i.e., if the battery **180** would have been charging, it is now charging at a higher rate, and if it would have been discharging, it will be discharging at a lower rate. Conversely, if the state of charge is over 50% the droop is slightly pushed up proportional to its deviation from 50%, causing the AC battery **180** to begin operating at a power level offset in the discharging direction; i.e., if the battery would have been charging, it is now charging at a lower rate and if it would have been discharging, it will now discharge at a higher rate. As a result of such a droop offset, those AC batteries **180** that have slightly different states of charge will have their droops offset slightly in different directions, resulting in a small amount of power that flows between the AC batteries **180** to equalize them.

The droop offset described herein may be employed in a variety of different types of droop control, including droop control for voltage forming inverters (as described below with respect to FIG. **3**) and droop control for current feeding inverters, which may also be referred to as "inverse droop" (as described below with respect to FIG. **4**).

FIG. **2** is a block diagram of a power conditioner controller **140** in accordance with one or more embodiments of the present invention. The power conditioner controller **140** comprises a transceiver **224**, support circuits **204** and a memory **206**, each coupled to a central processing unit (CPU) **202**. The CPU **202** may comprise one or more conventionally available microprocessors or microcontrollers; alternatively, the CPU **202** may include one or more application specific integrated circuits (ASICs). The power conditioner controller **140** may be implemented using a general purpose computer that, when executing particular software, becomes a specific purpose computer for performing various embodiments of the present invention. In one or more embodiments, the CPU **202** may be a microcontroller comprising internal memory for storing controller firmware that, when executed, provides the controller functionality described herein.

The transceiver **224** may be coupled to the power conditioner's output lines for communicating with the DER controller **108** and/or other power conditioners **110** using power line communications (PLC). Additionally or alternatively, the transceiver **224** may communicate with the DER controller **108** and/or other power conditioners **110** using other type of wired communication techniques and/or wireless techniques.

The support circuits **204** are well known circuits used to promote functionality of the CPU **202**. Such circuits include, but are not limited to, a cache, power supplies, clock circuits, buses, input/output (I/O) circuits, and the like.

The memory **206** may comprise random access memory, read only memory, removable disk memory, flash memory, and various combinations of these types of memory. The memory **206** is sometimes referred to as main memory and may, in part, be used as cache memory or buffer memory. The memory **206** generally stores the operating system (OS) **208**, if necessary, of the power conditioner controller **140** that can be supported by the CPU capabilities. In some embodiments, the OS **208** may be one of a number of commercially available operating systems such as, but not limited to, LINUX, Real-Time Operating System (RTOS), and the like.

The memory **206** stores various forms of application software, such as a power conditioner control module **210** and a phase lock loop module **212** for controlling, when executed, power conversion by the power conditioner **110**, and a droop control module **214** for employing, when executed, droop control techniques as described herein. The functionality of the droop control module **214** is described below with respect to FIGS. **3** and **4**. The droop control module **214**, when executed, operates in real-time or near real-time such that the corresponding energy storage device **112** autonomous charge balances with respect to the remaining energy storage devices **112**.

The memory **206** additionally stores a database **216** for storing data related to the operation of the power conditioner **110** and/or the present invention. In various embodiments, one or more of the power conditioner control module **210**, the phase lock loop module **212**, the droop control module **214**, and the database **222**, or portions thereof, are implemented in software, firmware, hardware, or a combination thereof.

FIG. **3** is a block diagram of a droop control module **314** in accordance with one or more embodiments of the present invention. As shown in FIG. **3**, the droop control module **314** (an implementation of the droop control module **214**) is coupled between a PLL module **312** (an implementation of the PLL module **212**) and a power conditioner control module **310** (an implementation of the power conditioner control module **210**). The droop control module **314** depicted in FIG. **3** provides droop control for voltage forming inverters—i.e., in those embodiments where the power conditioners **110** comprise the droop control module **314**, the power conditioners **110** are voltage forming inverters.

The droop control module **314** comprises multipliers **320** and **322**, adders **332**, **334**, **340**, **342** and **344**, subtractor **348**, and gain constant multipliers **324**, **326**, **328**, **330**, **336**, and **338**. During autonomous mode operation of the power conditioner **110**, the grid voltage Ugrid and the current being coupled to the grid by the power conditioner **110**, Igrid, are fed to the PLL **312**. Using the grid voltage Ugrid as a reference, the PLL **312** generates signals Id and lq, where Id represents the amplitude of the portion of the grid current Igrid that is in-phase with the grid voltage Ugrid and lq represents the portion of the grid current Igrid that is orthogonal to the grid voltage Ugrid, and couples the signals Id and lq to the multipliers **322** and **320**, respectively. The PLL **312** further generates the signal Ud which represents the peak value of the fundamental of the grid voltage Ugrid and couples the signal Ud to the multipliers **320** and **322**.

The multiplier **320** multiplies ½ Ling to generate the signal Q representing the reactive power component, and couples the signal Q to the gain constant multipliers **324** and **328**. The multiplier **322** multiplies ½ Ud*Id to generate the signal P representing the real power component, and couples the signal P to the adder **344** and to the gain constant multiplier **326**.

The droop control module **314** receives a signal SOC representing an estimate of the current state of charge of the energy storage device **112** coupled to the power conditioner **110**. Generally, the signal SOC is acquired from a state of charge (SOC) estimator embedded in the energy storage device **112** (e.g., the signal SOC may be obtained from a battery management unit of a battery **112** via an application programming interface API), although in some alternative embodiments the SOC estimator may be part of the power conditioner **110**. The received signal SOC is coupled to the subtractor **348**.

The subtractor **348** further receives a signal SOC target that represents a target value for a state of charge for the energy storage device **112**. The SOC target value is predetermined and is the same for each of the batteries **112** within a particular microgrid member **152** in order for the charge between the batteries **112** to autonomously equalize. In some embodiments, the SOC target value may be 50% state of charge such that, under normal conditions, all the batteries **112** within a particular microgrid member **152** are biased towards their 50% state of charge in order to optimize the balance between the batteries **112** being able to absorb excess power generated and to generate power when needed. In some other embodiments where the ability to power certain loads has a higher priority than being able to store excess generated power, the SOC target may be set at a value much greater than 50%.

The output from the subtractor **348** is coupled to the gain constant multiplier **346**, which has a gain constant of −kb which essentially determines the drift of the corresponding energy storage device **112**. Generally the value of kb is extremely small to prevent the SOC estimation from significantly affecting the dynamic characteristics of the power conditioner **110**. For example, if one energy storage device **112** within a microgrid member **152** is undercharged with respect to the other energy storage devices **112** (e.g., the other energy storage devices are 75% charged), it is desirable to have the one undercharged energy storage device **112** charge slightly faster or discharge slightly slower such that it slowly converges to the state of charge of the other energy storage devices **112**. In some embodiments where the power rating for the power conditioner **110** is ¼ of the KWH rating of the corresponding energy storage device **112** and the power conditioner **110** is 300 W conditioner, the value of kb may be 0.25 Watts/% for a 20% SOC difference and a desired 5 W difference in power between the energy storage devices **112** (i.e., 5 W/20%). In some other embodiment, the value of kb may be even smaller, for example 0.1 W/%.

The output from the gain constant multiplier **346** is a signal representing an SOC-based droop offset that is proportional to the state of charge of the corresponding energy storage device **112**. The SOC-based droop offset signal is coupled to the adder **344** for addition to the power term P. The resulting output signal from the adder **344**, Poffset, is coupled to the gain constant multiplier **330**.

The gain constant multipliers **324**, **326**, **328**, and **330** have respective gain constants X/Z, R/Z, −R/Z, and X/Z, where R, X and Z are impedance terms that are generally matched to the grid impedance at their point of common coupling, although they may be set using other techniques. In some embodiments where the grid impedance is mostly resistive, a typical value for X/Z may be on the order of 0.1, and a typical value for R/Z may be on the order of 10.0. In other embodiments where the grid impedance is mostly inductive, a typical value for X/Z may be on the order of 10.0 and a typical value for R/Z may be on the order of 0.1. Generally, X/Z and R/Z ranges from 0.1-10.0, although the range may vary depending on the type of system to which the power conditioners **110** are coupled.

The outputs from the gain constant multipliers **324** and **326** are coupled to the adder **332**; the adder **332** generates the signal Q' (which represents the modified reactive power) and couples Q' to the gain constant multiplier **336**. The gain constant multiplier **336** has a gain constant −kq, which is a reactive power droop gain depending on the size of the power conditioner **110** (i.e., depending on the amount of reactive power the power conditioner can deliver). In some embodiments where the system is a 240V system and the maximum reactive power delivery is 100 var, kq may have a value of 0.24V/var to minimize the voltage drop to +/−10%.

The output from the gain constant multiplier **336** is coupled to the adder **340**, along with a signal U0 that represents the target nominal voltage of the system (e.g., 240V AC or 230V AC). The output signal from the adder **340** is a signal Usrc representing the peak AC operating voltage for the power conditioner **110**; the signal Usrc is coupled to the power conditioner control module **310** for use by the power conditioner control module **310** in generating the output from the power conditioner **110**.

The outputs from the gain constant multipliers **328** and **330** are coupled to the adder **334**; the adder **334** generates the signal P' (which represents the modified real power) and couples P' to the gain constant multiplier **338**. The gain constant multiplier **338** has a gain constant −kp, which is a real power droop gain depending on the size of the power conditioner **110** (i.e., depending on the amount of real power the power conditioner can deliver). In some embodiments where the power conditioner **110** is a 300 W power conditioner operating at a frequency of 60 Hz, the value of kp is set at 0.01 Hz/W for a 5% droop. The output from the gain constant multiplier **338** is coupled to the adder **342**.

The output from the gain constant multiplier **338** is coupled to the adder **342**, along with a signal f0 that represents the target nominal frequency of the system (60 Hz or 50 Hz). The output signal from the adder **342** is a signal fsrc representing the AC operating frequency for the power conditioner **110**; the signal fsrc is coupled to the power conditioner control module **310** for use by the power conditioner control module **310** in generating the output from the power conditioner **110**.

In some alternative embodiments, a computer readable medium comprises a program that, when executed by a processor, performs the steps described with respect to FIG. **3** for determining the power conditioner droop control such that autonomous charge balancing of the energy storage devices **112** is achieved.

FIG. **4** is a block diagram of a droop control module **414** in accordance with one or more embodiments of the present invention. As shown in FIG. **4**, the droop control module **414** (an implementation of the droop control module **214**) is coupled between a PLL module **412** (an implementation of the PLL module **212**) and a power conditioner control module **410** (an implementation of the power conditioner control module **210**). The droop control module **414** depicted in FIG. **4** provides droop control for current feeding inverters—i.e., in those embodiments where the power conditioners **110** comprise the droop control module **414**, the power conditioners **110** are current feeding inverters.

The droop control module **414** comprises multipliers adders **420**, **422**, **436**, **438**, and **440**, gain constant multipliers **424**, **426**, **428**, **430**, **432**, **434**, and **442**, and subtractor **444**. The gain constant multipliers **428**, **430**, **432**, and **434** have gain constants X/Z, −R/Z, R/Z, and X/Z, respectively, which are set as previously described with respect to FIG. **3**.

During autonomous mode operation of the power conditioner **110**, the grid voltage Ugrid and the current being coupled to the grid by the power conditioner **110**, Igrid, are fed to the PLL **412**. Using the grid voltage Ugrid as a reference, the PLL **412** generates signals Ud and f, which respectively represent the peak value of the fundamental of the grid voltage Ugrid and the frequency of the grid voltage Ugrid, and couples the signals Ud and f to the respective adders **420** and **422**. Additionally, the PLL **412** utilizes the current Igrid to calculate the portion of the output current that is in phase (Id) and quadrature (Iq) with the grid voltage Ugrid for use in determining P and Q, although in other embodiments P and Q may be determined by a different means, such as a Direct Fourier Transform (DFT) or a simple averaging scheme where P=average (Ugrid[n]*Igrid[n]), S=average(Ugrid[n])*average(Igrid[n]), and Q~sqrt (S^2-P^2).

In addition to the signal Ud, the signal U0, which represents the target nominal voltage of the system (e.g., 240V AC or 230V AC), is coupled to the adder **420**. The output from the adder **420** is coupled to the gain constant multiplier **424**, which has a gain constant of ku, where the gain constant ku is the inverse of the gain constant kp described above with respect to FIG. **3**. The output signal from the gain constant multiplier **424**, Q', is coupled to the gain constant multipliers **428** and **432**.

In addition to the signal f, the signal f0, which represents the target nominal frequency of the system (60 Hz or 50 Hz), is coupled to the adder **422**. The output from the adder **422** is coupled to the gain constant multiplier **426**, which has a gain constant of kf, where the gain constant kf is the inverse of the gain constant kq described above with respect to FIG. **3**. The output signal from the gain constant multiplier **426**, P', is coupled to the gain constant multipliers **430** and **434**.

The output signals from the gain constant multipliers **428** and **430** are coupled to the adder **436** to generate the signal Q, which represents the reactive power component. The signal Q is coupled to the power conditioner control module **410**.

The output signals from the gain constant multipliers **432** and **434** are coupled to the adder **438** to generate the signal P, which represents the real power component. The signal P is coupled to the adder **440**. Additionally, a signal representing an SOC-based droop offset that is inversely proportional to the state of charge of the corresponding energy storage device **112** is coupled to the adder **440** for addition to the power term P. The SOC-based droop offset is obtained as described above with respect to FIG. **3**; i.e., an SOC estimate signal and an SOC target signal are coupled to a subtractor **444**, where the output of the subtractor **444** is coupled to the gain constant multiplier **442** to generate the SOC-based droop offset. The gain constant multiplier **442** has a gain constant or −kb as previously described. The resulting output signal from the adder **440**, Poffset, is coupled to the power conditioner control module **410**.

In some alternative embodiments, a computer readable medium comprises a program that, when executed by a processor, performs the steps described with respect to FIG. **4** for determining the power conditioner droop control such that autonomous charge balancing of the energy storage devices **112** is achieved.

FIG. **5** is a block diagram of a DER controller **108** in accordance with one or more embodiments of the present invention. The DER controller **108** comprises a transceiver **514**, support circuits **504** and a memory **506**, each coupled to a central processing unit (CPU) **502**. The CPU **502** may comprise one or more conventionally available microprocessors or microcontrollers; alternatively, the CPU **502** may include one or more application specific integrated circuits (ASICs). The DER controller **108** may be implemented using a general purpose computer that, when executing particular software, becomes a specific purpose computer for performing various embodiments of the present invention. In one or more embodiments, the CPU **502** may be a microcontroller comprising internal memory for storing controller firmware that, when executed, provides the controller functionality described herein.

The DER controller **108** generally communicates, via the transceiver **514**, with the power conditioners **110** using power line communications (PLC), although additionally or alternatively the transceiver **514** may communicate with the power conditioners **110** using other types of wired and/or wireless communication techniques. In some embodiments, the DER controller **108** may further communicate via the transceiver **514** with other controllers within the microgrid and/or with a master controller (not shown).

The support circuits **504** are well known circuits used to promote functionality of the CPU **502**. Such circuits include, but are not limited to, a cache, power supplies, clock circuits, buses, input/output (I/O) circuits, and the like.

The memory **506** may comprise random access memory, read only memory, removable disk memory, flash memory, and various combinations of these types of memory. The memory **506** is sometimes referred to as main memory and may, in part, be used as cache memory or buffer memory. The memory **506** generally stores the operating system (OS) **508**, if necessary, of the power conditioner controller **140** that can be supported by the CPU capabilities. In some embodiments, the OS **508** may be one of a number of commercially available operating systems such as, but not limited to, LINUX, Real-Time Operating System (RTOS), and the like.

The memory **506** stores various forms of application software, such as a DER control module **510** for controlling operations pertaining to the DER **106** (e.g., collecting performance data for the power conditioners **110**, generating control instructions for the power conditioners **110**, and the like). The memory **506** additionally stores a database **512** for storing data related to the operation of the DER **106**. In various embodiments, one or more of the DER control module **510** and the database **512**, or portions thereof, are implemented in software, firmware, hardware, or a combination thereof.

FIG. **6** is a block diagram of a component controller **128** in accordance with one or more embodiments of the present invention. The component controller **128** comprises support circuits **604** and a memory **606**, each coupled to a central processing unit (CPU) **602**. The CPU **602** may comprise one or more conventionally available microprocessors or microcontrollers; alternatively, the CPU **502** may include one or more application specific integrated circuits (ASICs). The component controller **128** may be implemented using a general purpose computer that, when executing particular software, becomes a specific purpose computer for performing various embodiments of the present invention. In one or more embodiments, the CPU **602** may be a microcontroller comprising internal memory for storing controller firmware that, when executed, provides the controller functionality described herein.

The support circuits **604** are well known circuits used to promote functionality of the CPU **602**. Such circuits include, but are not limited to, a cache, power supplies, clock circuits, buses, input/output (I/O) circuits, and the like.

The memory **606** may comprise random access memory, read only memory, removable disk memory, flash memory, and various combinations of these types of memory. The memory **606** is sometimes referred to as main memory and may, in part, be used as cache memory or buffer memory. The memory **606** generally stores the operating system (OS) **608**, if necessary, of the component controller **128** that can be supported by the CPU capabilities. In some embodiments, the OS **608** may be one of a number of commercially available operating systems such as, but not limited to, LINUX, Real-Time Operating System (RTOS), and the like.

The memory **606** stores various forms of application software, such as a component control module **610** for controlling, when executed, one or more functions of the corresponding component, and a droop control module **612** for employing, when executed, droop control techniques for operating the component.

The memory **606** additionally stores a database **612** for storing data related to the component. In various embodiments, one or more of the component control module **610**, the droop control module **612**, and the database **614**, or portions thereof, are implemented in software, firmware, hardware, or a combination thereof.

When a microgrid member **152** is disconnected from the local grid **132** and/or the utility grid **104**, the power conditioner controllers **140** and the component controllers **128** facilitate automatic control of the corresponding components. For example, the power conditioner control module **210** and the droop control module **214**, when executed, facilitate automatic control of the corresponding power conditioner **110**; e.g., the power conditioner control module **210** may monitor the power line frequency and voltage at the corresponding power conditioner **110** to ensure that the frequency and voltage stay within designated parameters.

By using such localized droop control, each component can autonomously optimize its operation with respect to the microgrid member **152**/overall microgrid **150**. For example, for the generator **130**, the component controller **128** may optimize the generation of power; for smart loads **118**, and the component controller **128** may optimize the consumption of energy (e.g., by controlling the energy consumed by individual loads either through throttling the flow or turning on and turning off various loads at certain times).

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is defined by the claims that follow.

The invention claimed is:

1. A method for autonomous charge balancing of a microgrid energy storage device, comprising:

obtaining, at a droop control module of a power conditioner coupled to an energy storage device in a microgrid, an estimate of a state of charge (SOC) of the energy storage device;

introducing a bias, the bias based on (I) the estimate of the SOC and (II) a target SOC value for each energy storage device of a plurality of energy storage devices in the microgrid, to a droop control determination made by the droop control module; and

generating, by the power conditioner, an output based on the droop control determination.

2. The method of claim **1**, wherein the bias is introduced to a real power term of the droop control determination.

3. The method of claim **1**, wherein the estimate of the SOC is obtained from an SOC estimator embedded in the energy storage device.

4. The method of claim **1**, wherein the energy storage device is a battery and the estimate of the SOC is obtained from a battery management unit of the battery.

5. The method of claim **1**, wherein the power conditioner determines the estimate of the SOC.

6. The method of claim **1**, wherein, when optimizing a balance between the plurality of every storage devices absorbing excess generated energy and providing energy when needed, the target SOC value is 50%.

7. The method of claim **1**, wherein, when powering one or more loads has a higher priority than storing excess generated energy, the target SOC value is greater than 50%.

8. Apparatus for autonomous charge balancing of a microgrid energy storage device, comprising:

a droop control module for providing droop control of a power conditioner coupled to an energy storage device in a microgrid, wherein the droop control module obtains an estimate of a state of charge (SOC) of the energy storage device and, based on (I) the estimate of the SOC and (II) a target SOC value for each energy storage device of a plurality of energy storage devices in the microgrid, introduces a bias in a droop control determination used by the power conditioner in generating an output.

9. The apparatus of claim **8**, wherein the bias is introduced to a real power term of the droop control determination.

10. The apparatus of claim **8**, wherein the estimate of the SOC is obtained from an SOC estimator embedded in the energy storage device.

11. The apparatus of claim **8**, wherein the energy storage device is a battery and the estimate of the SOC is obtained from a battery management unit of the battery.

12. The apparatus of claim **8**, wherein the power conditioner determines the estimate of the SOC.

13. The apparatus of claim **8**, wherein, when optimizing a balance between the plurality of every storage devices absorbing excess generated energy and providing energy when needed, the target SOC value is 50%.

14. The apparatus of claim **8**, wherein when powering one or more loads has a higher priority than storing excess generated energy, the target SOC value is greater than 50%.

15. A system for autonomous charge balancing of microgrid energy storage devices, comprising:

a plurality of power conditioners in a microgrid, each power conditioner of the plurality of power conditioners (i) coupled to a different energy storage device of a plurality of energy storage devices, and (ii) comprising a droop control module for providing droop control of the power conditioner, wherein the droop control module obtains an estimate of a state of charge (SOC) of the corresponding energy storage device and, based on (I) the estimate of the SOC and (II) a target SOC value for each energy storage device of the plurality of energy storage devices, introduces a bias in a droop control determination used by the power conditioner in generating an output.

16. The system of claim **15**, wherein the bias is introduced to a real power term of the droop control determination.

17. The system of claim **15**, wherein the estimate of the SOC is obtained from an SOC estimator embedded in the corresponding energy storage device.

18. The system of claim **15**, wherein the corresponding energy storage device is a battery and the estimate of the SOC is obtained from a battery management unit of the battery.

19. The system of claim **15**, wherein the power conditioner determines the estimate of the SOC.

20. The system of claim **15**, wherein, when optimizing a balance between the plurality of every storage devices absorbing excess generated energy and providing energy when needed, the target SOC value is 50% and wherein, when powering one or more loads has a higher priority than storing excess generated energy, the target SOC value is greater than 50%.

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